SEARCHING FOR AN INTERMEDIATE-MASS HIGGS AND NEW PHYSICS IN TWO-PHOTON COHERENT PROCESSES AT THE LHC.

Elena Papageorgiu
Laboratoire de Physique Théorique et Hautes Energies*
Université de Paris XI, bâtiment 211, 91405 Orsay Cedex, France

Abstract

We reexamine the prospects for searching for a neutral Higgs boson in the intermediate-mass range and physics beyond the standard model, using the proton- and ion-beam facilities of the LHC to study coherent two-photon processes. Considering realistic design luminosities for the different ion beams, we find that beams of light-to-medium size ions like calcium will give the highest production rates. With a suitable trigger and assuming a b-quark identification efficiency of 30% and a $b\bar{b}$ mass resolution of 10 GeV one could expect to see a Higgs signal in the $b\bar{b}$ channel with a 3-4 σ statistical significance in the first phase of operation of the LHC with beams of calcium. The discovery potential for light supersymmetric particles is as promissing. The study of such very "quiet" final state topologies in heavy ion collisions could even lead to the discovery of a new phase of QED.

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(I) An intermediate-mass Higgs in coherent NN and pp collisions at the LHC.

The search for the Higgs particle(s) of the standard model (or its supersymmetric version) beyond the discovery potential of LEP2 has become one of the major objectives of the LHC. The intermediate-mass range $M_H \simeq 80 - 130$ GeV is particularly challenging for both theory and experiment. Here, simultaneous searches in different channels of hard pp collisions and a minimum of three years of operation at the initial luminosity $L_p \simeq 10^{33} cm^{-2} s^{-1}$ will be needed in order to establish a 3-4 σ signal, or, one will have to wait for the design luminosity $L_p^d \simeq 10^{34} cm^{-2} s^{-1}$ by the year 2008 [1].

A different kind of Higgs- and SUSY-particle production, which would make use of the ion beam facilities at the LHC, was proposed some time ago [2], namely, the two-photon production in the coherent electromagnetic field of nucleus nucleus collisions in which the nuclei $N_{i=1,2}$ would "ideally" remain intact :

$$N_1 N_2 \to N_1 N_2 + X \qquad X = H, \tilde{\ell}^+ \tilde{\ell}^-, \tilde{\chi}^+ \tilde{\chi}^-, \cdots , \qquad [1]$$

where $\tilde{\ell}^+ \tilde{\ell}^-$ and $\tilde{\chi}^+ \tilde{\chi}^-$ refers to a pair of sleptons and charginos respectively. Triggering exclusively on such events would imply cross sections which scale with the nuclear charges as $Z_1^2 Z_2^2$ and a much cleaner (purely photonic) environement for particle searches than the usual hadronic background of pp collisions. The "coherency" of the collision can be guaranteed by imposing cuts on the impact parameter space of the two nuclei (Fig 1) :

$$b_i > R_i \qquad \text{and} \qquad |\vec{b_1} - \vec{b_2}| > R_1 + R_2 \, , \qquad [2]$$

$i.e$, treating the nuclei as two nonoverlapping, "hard" and "opaque" discs with radii $R_i \simeq r_0 A_i^{1/3}$ ($r_0 \simeq 1.2$ fm) [3,4]. One should notice that when nuclei or nucleons overlap, elastic scattering is partly the "shadow" of inelastic processes. Therefore the presence of the nuclear elastic form factor is not sufficient to

exclude strong interaction processes taking place after the photons have been emitted from the nuclei. The constraints of eq.(2) imply almost real photons, $q_i^2 < \frac{1}{R_i^2}$ and the factorization of the cross section in the underlying subprocess: $\sigma(\gamma\gamma \to X)$ times the two-photon flux [3]

$$\frac{dL_{\gamma\gamma}}{dW^2} = \int\int f_1(\omega_1, b_1)\ f_2(\omega_2, b_2)\ \Theta(B - R_1 - R_2) \\ \times \delta(W^2 - 4\omega_1\omega_2)\ d\omega_1\ d\omega_2\ d^2b_1\ d^2b_2 \quad [3]$$

where $f_i(\omega_i, b_i)$ is the number of photons with energy ω_i at a fixed impact and $W^2 = 4\omega_1\omega_2$ is the invariant mass squared.

For a Higgs in the intermediate-mass range which would predominantly decay into a $b\bar{b}$ pair the signal-to-background ratio is sizably more favourable in coherent collisions than in hard-scattering NN and pp collisions :

$$\begin{aligned} (S/B)_{COH} &\equiv \frac{\gamma\gamma \to H \to b\bar{b}}{\gamma\gamma \to b\bar{b}} \simeq 10^{-1} \\ (S/B)_{HS} &\equiv \frac{gg \to H \to b\bar{b}}{gg \to b\bar{b}} \simeq 10^{-3} - 10^{-4}\,, \end{aligned} \quad [4]$$

assuming a $b\bar{b}$ resolution of $\mathcal{R} \simeq 10$ GeV. This is mainly due to the difference in electric charge between the bottom and the top quark, the latter being the dominant contribution in the $\gamma\gamma \to H$ loop. Imposing cuts on the rapidity and the transverse momentum of the b jets can improve significantly these ratios [5], *e.g.*, for a $p_T \geq 0.4 M_H$:

$$\begin{aligned} (S/B)_{COH} &\simeq \frac{1}{5} \qquad 100\mathrm{GeV} < \mathrm{M_H} < 120\mathrm{GeV} \\ &\simeq \frac{1}{3} \qquad 120\mathrm{GeV} < \mathrm{M_H} < 150\mathrm{GeV} \end{aligned} \quad [5]$$

To take advantage of the very favourable signal-to-background ratio in coherent processes one would need a powerful veto trigger on spectator jets, coming from diffractive dissociation and/or nucleon fragmentation of the beam,

which will go in the very forward (backward) direction and will have a typical transverse momentum of a few GeV. If instead of ion beams one would use proton beams, tagging could be possible. An extension of the ALICE detector with forward spectrometers for studying among other physics genuine two-photon processes in pp and NN collisions is currently under discussion [6]. The production of muon pairs would be best suited for measuring the two-photon flux in heavy-ion collisions already at the present energy of the SPS, where one could also study the spectroscopy of low-energy resonances like the η'.

The crucial point of course is whether the production rate in coherent collisions is large enough to see a signal with a statistical significance of say 3-4 already during the first operational phase of the LHC, and with which type of beam one would do the best job. When this mechanism was originally proposed it was thought that the use of heavy ions like Pb would be more advantageous due to the higher charge. As a matter of fact, in $Pb-Pb$ collisions the Higgs-boson production is as large as a few tens of picobarns [Fig. 3] and comparable to the one in hard pp collisions. On the other hand, a more recent study [7] has shown that the maximum achievable luminosity L_b is for beams of realy heavy ions several orders of magnitude lower than for lighter ions or protons (Table 1) due to large intra beam effects.

	p-p	**Ca-Ca**	**Pb-Pb**
$\mathbf{L_b[cm^{-2}s^{-1}]}$	$10^{33}-10^{34}$	5×10^{30}	5×10^{26}
$\mathbf{E_b[TEV]}$	7	140	574
$\mathcal{W}_\mathbf{0}\mathbf{[GEV]}$	3×10^3	370	170
Ev./y	- (30-70)	20-50	$\ll 1$
$\mathbf{S/\sqrt{S+B}}$	$-(6-7)$	$5-6$	—
$\mathbf{(S/\sqrt{S+B})^*}$	– (3-4)	3-4	—

Table 1 : The beam luminosity L_b and the energy per beam E_b for different type of collisions at the LHC, from Ref. [7]. The mass range $\mathcal{W}_0$ which can be typically explored via coherent two-photon processes. The number of events per year for $\gamma\gamma\to H\to b\bar{b}$ and $M_H\simeq 80$ - 180 GeV. The statistical significance

$S/\sqrt{S+B}$ for the same process and $M_H \simeq$ 100-130 GeV after 3-4 years of running. The same as above but assuming 30 % b-detection efficiency.

Another reason why lighter ions or even protons may be preferable is the following. The typical mass range which can be explored via two-photon coherent pocesses in hadron collisions is limited to :

$$\mathcal{W}_0 = \frac{2\gamma}{\sqrt{R_1 R_2}} \,, \qquad [6]$$

simply because the number of equivalent photons in the electromagnetic pulse created by relativistic nuclei is decreasing rapidly for $\omega > \gamma/R$. At the LHC where the maximum energy of a proton beam will be $E_p = 7$ TeV, the maximum energy of an ion beam will be $E_{ion} = E_p Z$ and $\gamma \simeq 7.5 \frac{Z}{A} \, [\frac{\mathrm{TeV}}{\mathrm{n}}]$. Typically the mass range which can be explored with different type of beams is shown in Table 1. For the same reason the two-photon flux is decreasing rapidly as the nuclear size increases for invariant masses close to $\mathcal{W}_0$,

$$\frac{dL_{\gamma\gamma}}{dW^2} = \frac{\mathrm{const.}}{W^2} \times \mathcal{F}\left(\frac{\mathcal{W}_0}{W}\right) \,. \qquad [7]$$

A comparison of the two-photon luminosity function $dL/dW = L_b \times \frac{dL_{\gamma\gamma}}{dW}$ for heavy ions (Pb-Pb), medium-size ions (Ca-Ca) and protons (p-p) shows that beams of light-to-medium-size nuclei would be the better choice. The upper and lower pp curves correspond to a cut-off of $R \simeq 0.2$ fm, which is the proton radius as determined from elastic electron scattering, and, a cut-off $R \simeq 1$ fm at the outer edge of the very extended proton surface. They show that applying less stringent cuts one would gain a factor ten more in $\gamma\gamma$ luminosity, at the expense of some hadronic background. Since a veto detector on spectator jets cannot exclude partial or full dissociation of the nuclei, very soft hadronic processes, and final state interactions, the precise value of the theoretical cut-off can be chosen only in connection with the performance of the trigger for which a simulation would be needed [8].

The total cross section for producing an intermediate-mass Higgs in coherent $Pb-Pb$, $Ca-Ca$ and $p-p$ csions is shown in Fig. 3 and the corresponding event rates for one year of full running are given in Table 1. The event rate in $Ca-Ca$ collisions is comparable to the one in $p-p$ collisions at the higher design luminosity. For such collisions the statistical significance that can be achieved after one year will be $S/\sqrt{S+B} \simeq 2$, but, assuming realistic values for the b-detection efficiency of $\epsilon = 30\%$ reduces the signal-to-background ratio of eq.(5) to:

$$
\begin{aligned}
(S/B)^{\star}_{COH} &\simeq \frac{1}{10} \qquad 100\mathrm{GeV} < \mathrm{M_H} < 120\mathrm{GeV} \\
&\simeq \frac{1}{5} \qquad 120\mathrm{GeV} < \mathrm{M_H} < 150\mathrm{GeV}\,.
\end{aligned}
\qquad [8]
$$

With this one could reach the same statistical significance as in the hard-scattering pp channels, namely $(S/\sqrt{S+B})^{\star} \simeq 3-4$ within the operational phase I of the LHC, *i.e*, within three to four years.

(II) Two-photon production of non-strongly interacting SUSY particles at the LHC.

In contrast to coloured supersymmetric particles (squarks and gluinos) which will be produced copiously at the LHC, the search for the non-strongly interacting supersymmetric particles (sleptons and charginos) in the decay cascades of the former will be particularly challenging in hard pp collisions. Searches in the much cleaner environement of coherent hadron collisions, and given the fact that their coupling to photons is well known -charginos couple as fermions (f^+f^-) and sleptons as scalars (S^+S^-)-, could be more promissing. The corresponding cross sections for Ca-Ca collisions are shown in Fig. 4. For charginos with a mass $100GeV \leq M_{\tilde{\chi}} \leq 150GeV$ one should expect at least $(\mathbf{50-5})\mathbf{Ev./y}$ while the sleptons rate in the mass range $100GeV \leq M_{\tilde{\ell}} \leq 120GeV$ will be smaller, $(\mathbf{15-5})\mathbf{Ev./y}$. According to Fig. 2 the same rates are expected also for coherent pp collisions for an integrated luminosity of $100fb^{-1}$.

Our predictions, for which the impact parameter cut-off was used in order to exclude all strong absorbtion processes, lie below the predictions in ref.[9] where the elastic formfactor of the proton was used. For a comparision of the different approaches see ref. [3]. The background from $\gamma\gamma \to W^+W^-$ and $\gamma\gamma \to \mu^+\mu^-$, after rapidity and p_T cuts have been applied, can be successfully suppressed with respect to the signal by requiring the transverse momenta of the W's or better of the μ's not to balance (*e.g.* within 10 GeV) -as expected from the coherency condition of eq.(2)- due to the escaping invisible LSP's (the lightest stable supersymmetric particle) [9]. In this way and assuming an error of ± 5 GeV the search for a light chargino (slepton) in coherent collisions of protons and light-to-medium size nuclei should become a feasible task.

(III) Conclusions

Using the proton and ion beam facilities at the LHC to study very "quiet" final state topologies, so-called coherent processes, could lead to some nice surprises, ranging from the discovery of a 100-130 GeV mass Higgs boson and light supersymmetric particles, to the yet more exotic possibility of a new (nonperturbative, chiral) phase of QED reserved to heavy ions only [10].

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Figure Captions

Fig. 1 Higgs production in coherent nucleus nucleus collisions Feynman graph (diagram on the left) and impact parameter plane (diagram on the right).

Fig. 2 The two-photon luminosity $dL/dW = L_b \times dL_{\gamma\gamma}/dW$ in coherent NN and pp collisions. The values for L_b are shown in Table 1. The upper and lower dotted curves correspond to a different impact parameter cut-off for pp collisions for which the lower luminosity was used. From ref.[8].

Fig. 3 The total cross-section for the production of the standard model Higgs via two-photon fusion in coherent NN collisions (3a) and in pp collisions at the upgrated luminosity (3b). From ref.[8].

Fig. 4 The two-photon production of a pair of charginos (upper curve) and a pair of sleptons (lower curve) as a function of the particles masses in coherent Ca-Ca collisions at the LHC.